National Aeronautics and Space Administration

Unmanned Aircraft Systems (UAS) Integration in the National Airspace System (NAS) Project

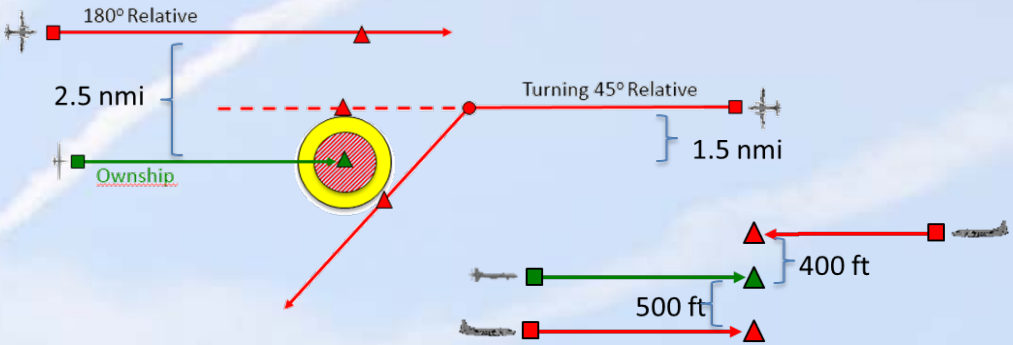
Integrated Test and Evaluation Flight Testing Overview

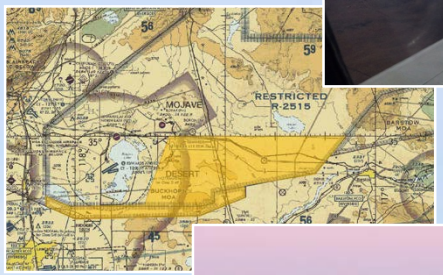
www.nasa.gov

June 2017

Integrated Test and Evaluation (IT&E) Goals

- Conduct simulations and integrated flight tests in a relevant environment to collect required research data





- Develop and adapt the test environment infrastructure to conduct UAS research

IT&E Objectives

- Provide an adaptable test infrastructure for simulation and flight test research
  - › Leverage existing and/or modify aircraft
  - › Leverage airspace
  - › Leverage and build upon existing NASA Live Virtual Constructive (LVC) system
  - › We are not building a prototype operational system
- Execute simulations and flight tests
  - › Concept development
  - › Verification and validation (V&V)
- Technology integration
- Maintain data collection archive

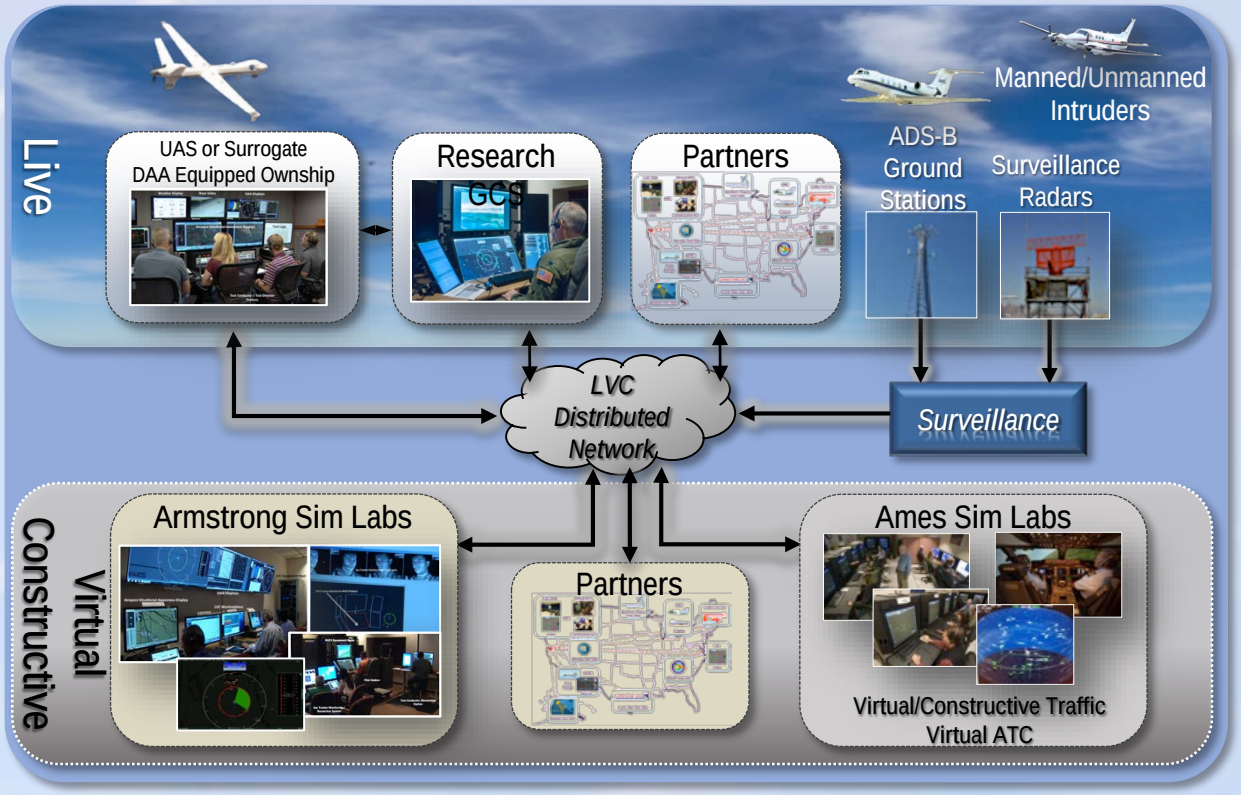
Live Virtual Constructive (LVC) Objectives

Distributed

- To support asset usage where they exist
- External partner support

Adaptable

- Support for dynamic research requirements
- Utilize inputs from multiple surveillance sources (air and ground)
- Emulate data sources and features



Extensible

- Use for simulation and live flight testing
  - Reduces risk moving between simulation and flight
- Across NASA centers
- Tie in UAS collaborators

IT&E Capabilities

Encounter Design and Range Coordination

Airspace Planning

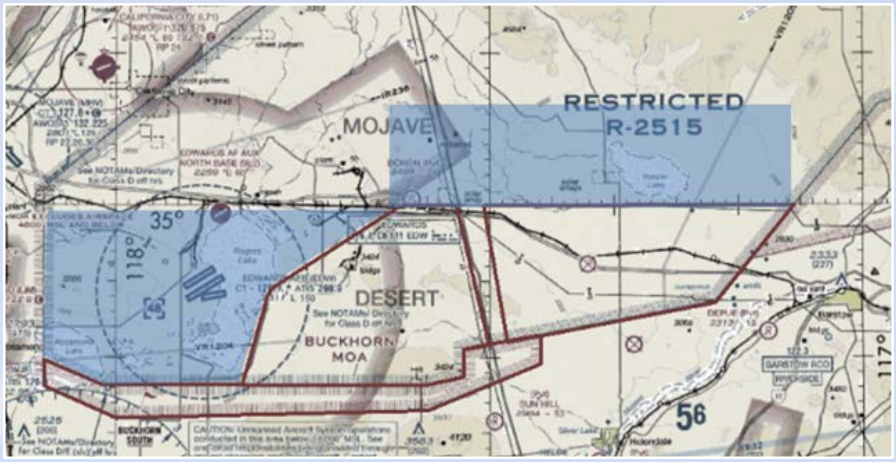
- Primarily Mercury Spin, 4 Corners and Buckhorn Military Operating Area (MOA) (red outline)
- 1,000 feet AGL (4.2K feet) to 20K feet MSL
- Extensions (west/north) may be requested real time for encounters that need the additional airspace
- Operations outside of test area (blue shaded areas) are planned to be performed early (before 0800) when airspace is relatively empty
- Operations between 0600 and 0700 are under Joshua control and have less geographical constraints

Coordination with Edwards Range

- Coordination of range/operating area borders and UAS keep out zones
- Ikhana must remain within Range (R)-2515 at all times
- Intruder aircraft can use Buckhorn MOA, plus areas shaded in blue

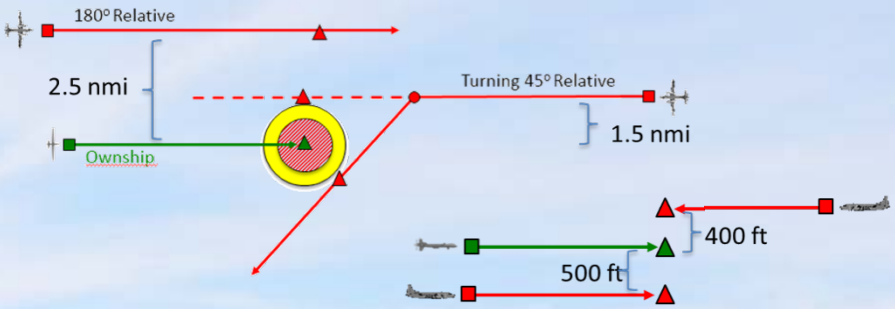
Encounter design accomplished by operations working group with researchers and partners

- Encounter requirements coordinated with System Safety Working Group to ensure flight safety
- Mitigations designed into flight test planning (safe separation, training, testing, offsets, procedures, etc.)



Airspace Extensions (Blue Shaded Areas)

- Conducted early 0600-0800 preferably
- Pre-coordinated 24-48 hours in advance
- Requested real-time with SPORT (after 0700)

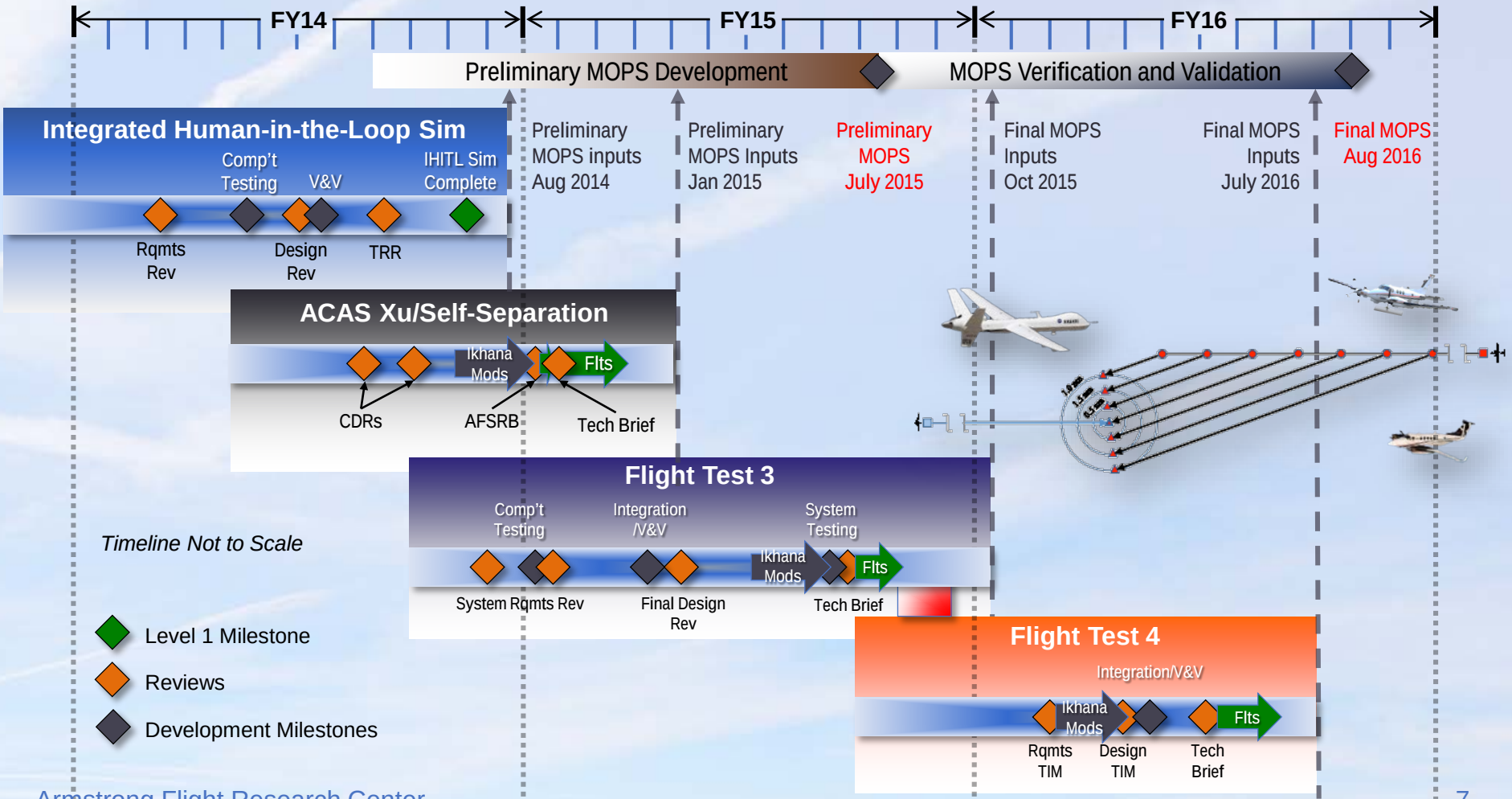


Completed Flight Tests

Completed Flight Tests

Risk Reduction Approach to Integrated Test Flow

- Each test built upon the previous and reduced future risk
- Lessons learned applied from one test to the next



IT&E Flight Test Summary

Ownship – Ikhana

- Build-up of detect and avoid (DAA) system (air-to-air [A/A] radar/Automatic Dependent Surveillance-Broadcast (ADS-B]/traffic alert and collision avoidance system [TCAS]) to meet researcher requirements
- Ikhana logged more than 190 hours flight time for airborne collision avoidance system (ACAS) Xu, Flight Test (FT)3, and FT4 data collection

Intruder Aircraft (seven total aircraft)

- Met researcher objectives to represent many classes of aircraft
  - Low-speed, mid-speed, high-speed
  - Cooperative versus non-cooperative
  - Small, medium, large radar cross section
- Equipped four aircraft with required surveillance systems
- Coordinated 25 crew members from three organizations
  - NASA, U.S. Air Force, Honeywell

Flight Test Stats

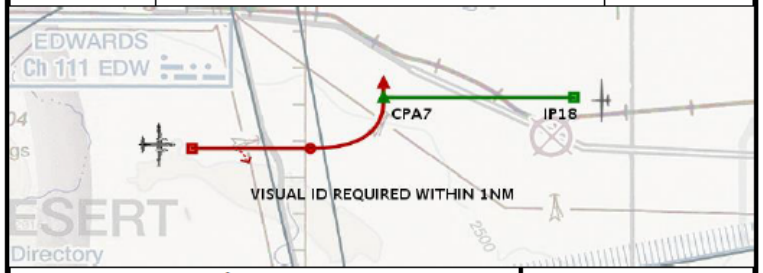
- **ACAS Xu:** 9 flights, 170 encounters flown (one intruder)
- **FT3:** 11 flights, 212 encounters flown (multiple intruders)
- **FT4:** 19 flights, 321 encounters flown (up to four intruders)

Aircraft	Intruder DAA Encounter Sensor Suite Configuration				
	ADS-B (1090 IN/OUT)	Mode S Transponder	TCAS I	TCAS II (v7.1)	DGPS
HW King Air (N3GC)	X	X		X	X
AFRC T-34C (NASA 865)	X	X	X		X
AFRC TG-14 (NASA 856)	X	X			X
AFRC King Air (NASA 801)	X	X	X		X
AFRC G-III (NASA 808)	X	X		X	X
USAF C-12 (not shown)		X		X	X

Flight Test 4 supporting aircraft

FT4 Flight Test Card

FT4 DAA Scripted	A/C: NASA 870	S/N: 270	VERSION 4
CARD#	**270-Sc-S3M**		OWNSHIP



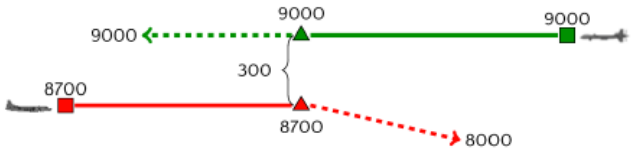
1. TC announces COMEX time.
2. Announce "<Callsign>, IP Inbound, altitude & special procedure review" crossing IP.
3. On condition at IP.
4. TC calls "terminate" when run complete.
5. TC announces next Card Number.

LOST LINK MISSION: 16

DECONFLICTION ALT: 9000

ADS-B IN:	OFF	IFF	TCAS	
DISPLAY:	JADEM	DAIDA.	CPDS	
MANEUVER:	OFF	Advisory	AUTO	
SENSOR SELECT:	Tracker	Radar	ADS-B	TCAS

ABORT PROCEDURE: 9000 — NAV TO LL WPT



COMEX TIME:

IP WIND:

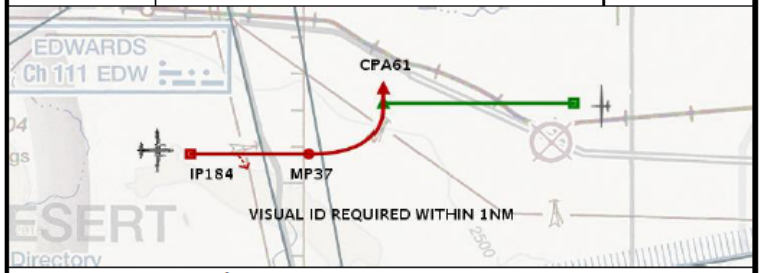
WPT	LATITUDE	LONGITUDE	ALT / V/V	DIST / MC	KGS	LEG TIME
IP18	N34° 57.09'	W117° 21.52'	9000	5.0	150	2+00
	N34° 57' 05.4"	W117° 21' 31.2"	0	258		
CPA7	N34° 57.09'	W117° 27.62'	9000	0.0	150	
	N34° 57' 05.4"	W117° 27' 37.2"	0	258		

NOTES: Ownship maneuver. Follow CPDS Guidance. Or, follow TCAS RAs if generated.

TOLERANCE: ± 8 sec ± 5 kts

Maneuver:	YES	NO	
Guidance:	BANDS	WCR	TCAS
Direction:	Up and/or lateral		
Limit:	NO DESCEND		

FT4 DAA Scripted	A/C: NASA865	S/N: 270	VERSION 4
CARD#	**270-Sc-S3M**		INTRUDER 1



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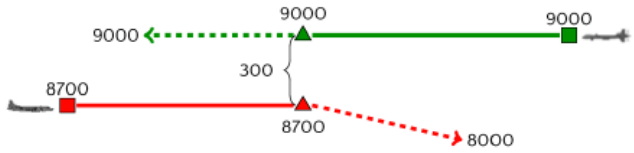
4. TC calls "terminate" when run complete.
5. TC announces next Card Number.

DECONFLICTION ALT: 8000

ABORT PROCEDURE: 8000 — RIGHT 123



COMEX TIME:

IP WIND:

WPT	LATITUDE	LONGITUDE	ALT / V/V	DIST / MC	KGS	LEG TIME
IP184	N34° 55.69'	W117° 33.74'	8700	5.7	180	2+00
	N34° 55' 41.4"	W117° 33' 44.6"	0	078		
MP37	N34° 55.69'	W117° 29.95'	8700	2.7	180	
	N34° 55' 41.4"	W117° 29' 57.0"	0	123		
CPA61	N34° 57.49'	W117° 27.62'	8700	0.0	180	
	N34° 57' 29.4"	W117° 27' 37.2"	0	168		

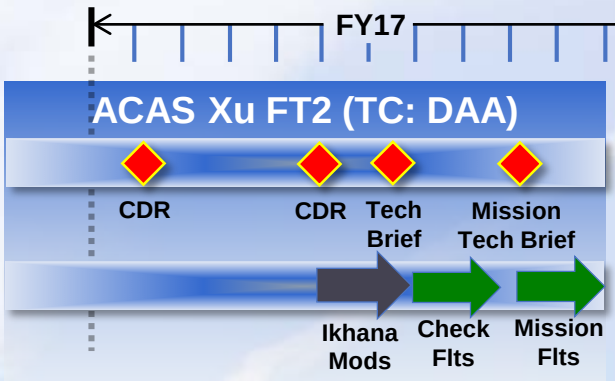
NOTES: Expect Ownship maneuver. Intruder ½ standard rate turn. Turn to maintain sight.

TOLERANCE: ± 8 sec ± 5 kts

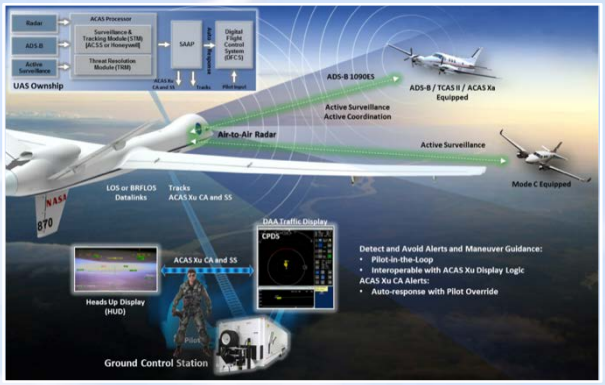
FT4 Quad Video Recording

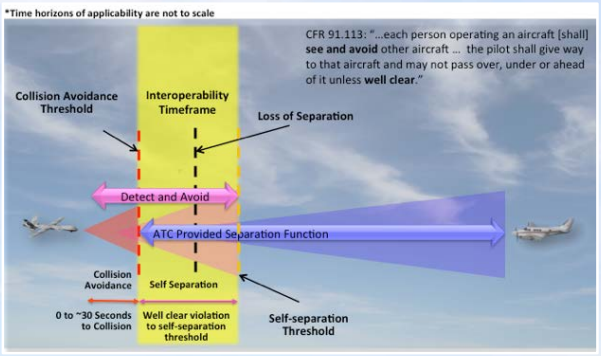
In Progress/Upcoming Flight Tests

IT&E Integrated Test Flow – ACAS Xu FT2



Development Activities | Flight Tests | Aircraft Mods | Review/Tech Brief





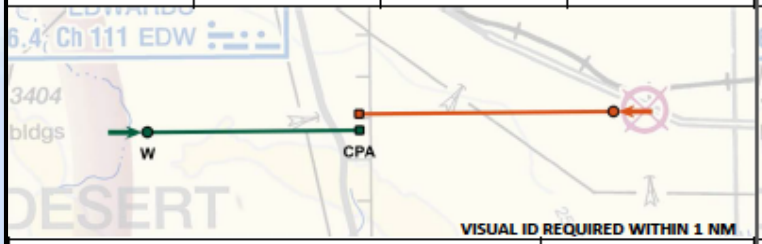
Well clear and collision avoidance functions integrated into one algorithm

ACAS Xu FT2	
Purpose	▪ Validate modeling and simulations ▪ Demonstrate system behavior integrated on prototype avionics and UAS ▪ Collect flight test data for performance evaluations and future research and development (R&D)
Approach	▪ Increased functionality > Combined horizontal and vertical maneuvers against multiple intruders > Resolution advisory (RA) logic accounts for sensor quality and ownship performance limitations
Test Duration	June-July 2017: 10-12 flights (~150 encounters)
Tech Transfer	▪ Contribute to ACAS Xu minimum operational performance standards (MOPS) development
Project Benefit	▪ Continued collaboration with the Federal Aviation Administration (FAA) to mature the ACAS Xu software in support of the ACAS Xu MOPS development

ACAS Xu FT2 Flight Test Card

Card #	HCHK-09	Ikhana Ownship

INITIAL ALT	INITIAL SPEED	INITIAL WAYPOINT	RA RESPONSE:
10000 FT	150 KGS	W	None



- Ikhana coordination MASTER. Set ALTERNATE Mode S OCTAL 50311031, call sign N200AX.
- RA RESPONSE: Do not respond
- POTENTIAL ALERT TYPES: Vertical or Horizontal
- ADDITIONAL INSTRUCTIONS: None

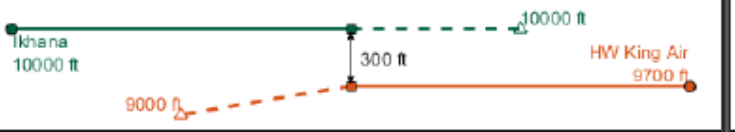
LOST LINK: 3

DECONFLICTION ALT: 10000

MANEUVER:	ADVISORY	AUTO	
STM:	HON	FAA	
TEST MODE:	65: DAA Mode		
SENSOR:	Active	ADSB	ATAR
INHIBIT:	Turn	Climb	

ABORT PROCEDURE:

10000	NAV to LL WPT



COMEX TIME: IP WIND:

WPT	LATITUDE	LONGITUDE	ALT V/V	DIST MC	KGS	LEG TIME (TOTAL REM.)
W	N34° 55.64'	W117° 36.37'	10000	5.0	150	02:00
	N34° 55' 38.4"	W117° 36' 22.1"	0	078		(02:00)
CPA	N34° 55.64'	W117° 30.29'	10000	0.0	150	End
	N34° 55' 38.5"	W117° 30' 17.4"	0	078		

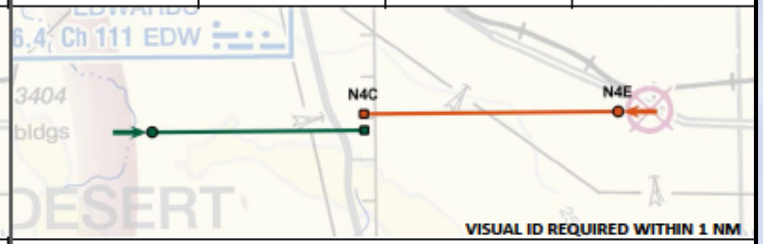
NOTES: Honeywell ACAS Xu implementation required. Lateral separation: 0.4 nmi

Xu FT2 NASA@Edwards
Version 3.2, Created 5/3/2017 | Priority 1

HCHK-09

Card #	HCHK-09	HW King Air Intruder

INITIAL ALT	INITIAL SPEED	INITIAL WAYPOINT	RA Mode
9700 FT	180 KGS	N4E	TA/RA

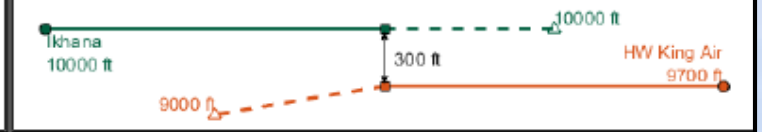


- RA RESPONSE: Do not respond
- ADDITIONAL INSTRUCTIONS: None

DECONFLICTION ALT: 9000

ABORT PROCEDURE:

9000	Right



COMEX TIME: IP WIND:

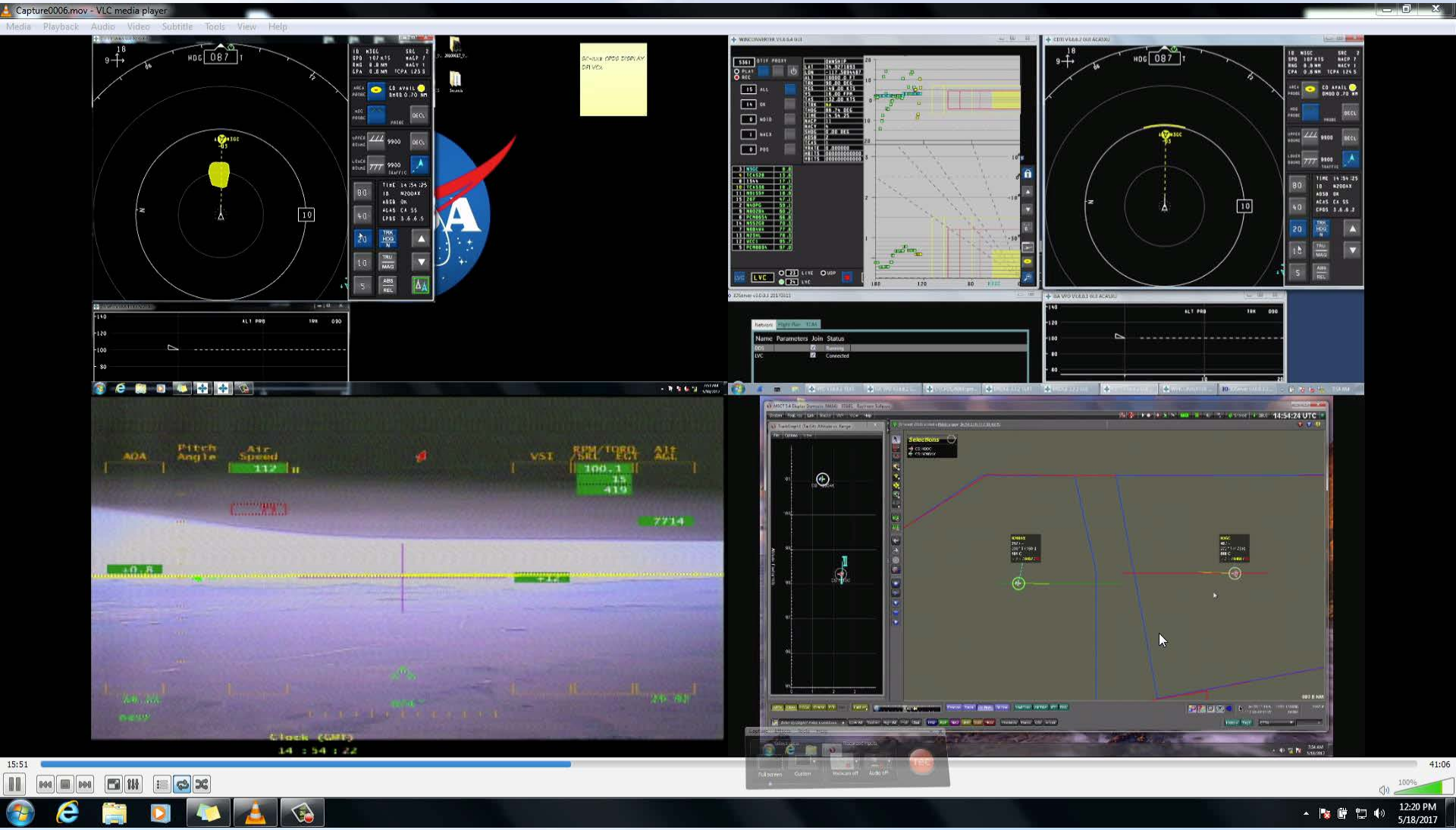
WPT	LATITUDE	LONGITUDE	ALT V/V	DIST MC	KGS	LEG TIME (TOTAL REM.)
N4E	N34° 56.04'	W117° 22.99'	9700	6.0	180	02:00
	N34° 56' 02.4"	W117° 22' 59.7"	0	258		(02:00)
N4C	N34° 56.04'	W117° 30.29'	9700	0.0	180	End
	N34° 56' 02.6"	W117° 30' 17.4"	0	258		

NOTES: Lateral separation: 0.4 nmi

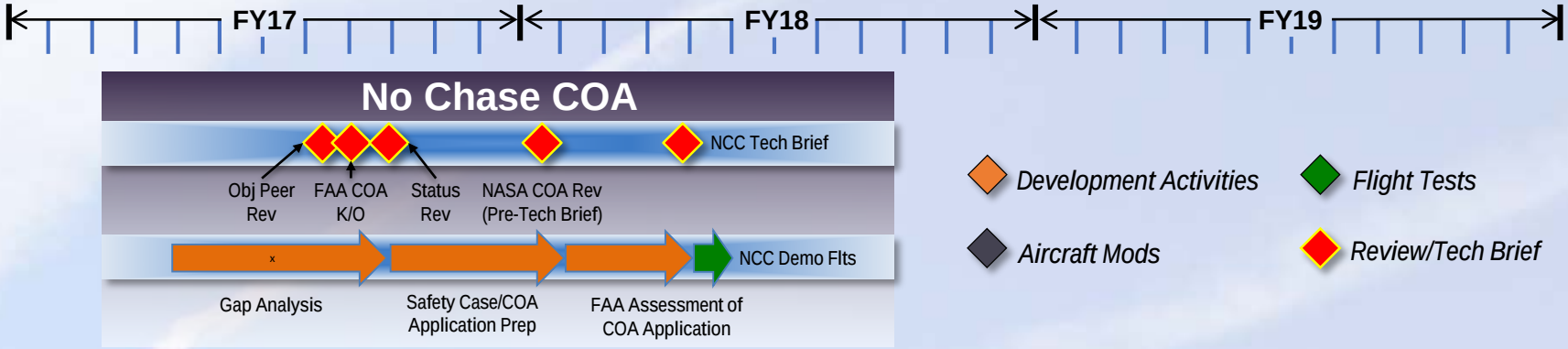
Xu FT2 NASA@Edwards
Version 3.2, Created 5/3/2017 | Priority 1

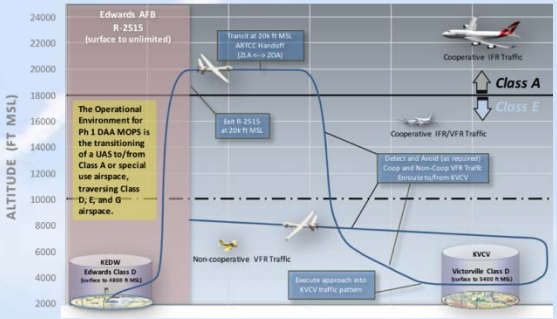
HCHK-09

ACAS Xu FT2 Quad Video Recording



No Chase Certificate of Authorization (COA)



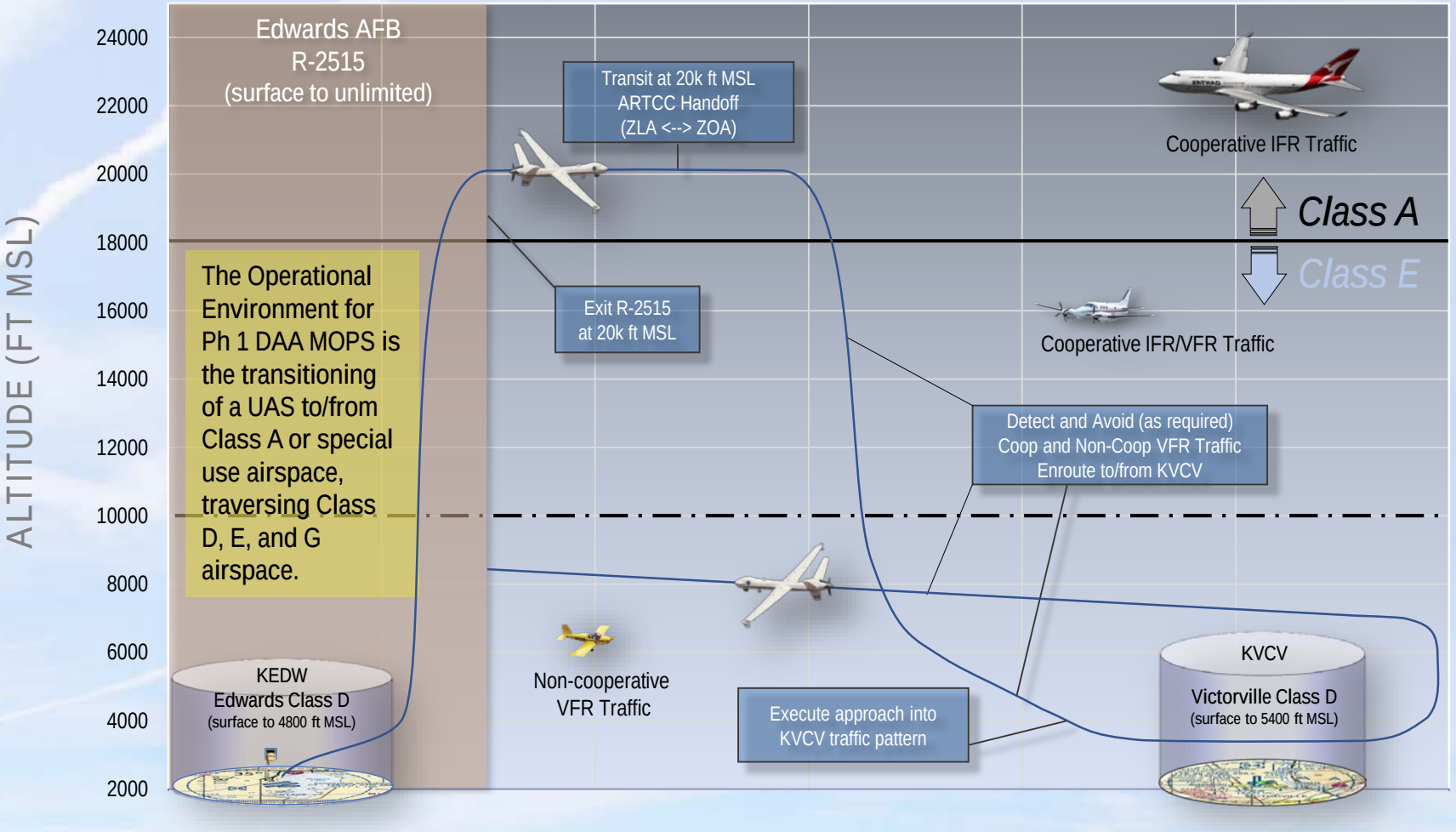


No Chase COA Demonstration	
Purpose	▪ Obtain COA from FAA to fly Ikhana UAS without safety chase in multiple classes of airspace, including Class A, D, and E ▪ Demonstrate UA transitioning to/from Class A or special use airspace (SUA) to Class E and Class D employing the Phase 1 detect and avoid (DAA) and A/A radar MOPS systems as alternate compliance for 14CFR 91.113b
Approach	▪ Complete gap analysis and safety case analysis justifying alternative method of compliance with Federal Aviation Regulation (FAR) Part 91.113 ▪ Work in partnership with General Atomics Aeronautical Systems Inc. (GA-ASI) to secure use of GA-ASI DAA system as primary airborne de-conflicting tool
Test Duration	▪ February 2018: 2-3 flights
Tech Transfer	▪ Demonstrate Phase 1 DAA and radar MOPS research findings through a “Capstone” event
Project Benefit	▪ Demonstration of UAS-NAS Phase 1 DAA technologies

No Chase Aircraft COA Flight Demonstration

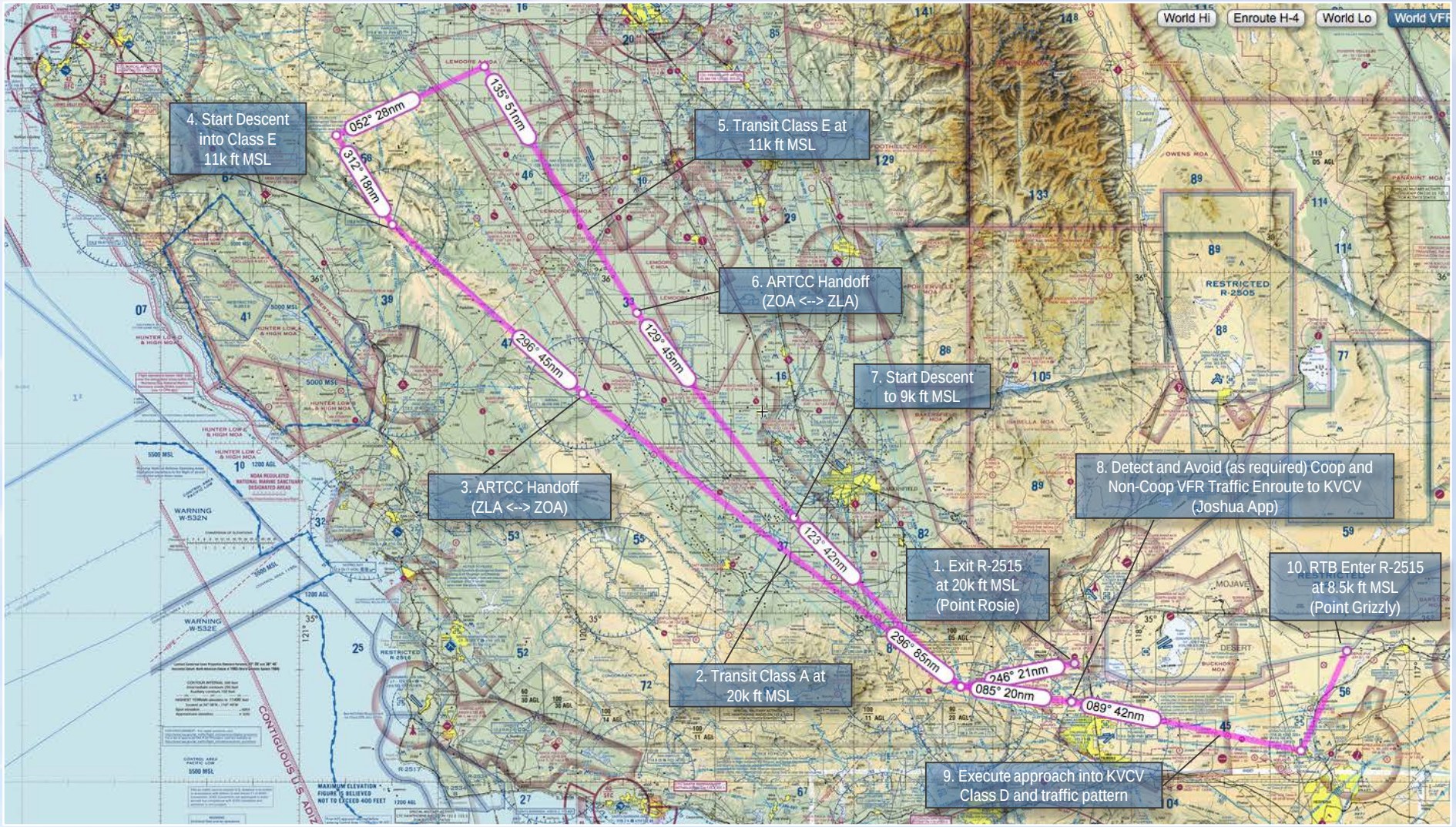
Concept of Operations (CONOPS)

Objective: Demonstrate UA transitioning to/from Class A or SUA to Class E and Class D employing the Phase 1 DAA and air-to-air radar MOPS systems as alternate means of compliance for 14 CFR 91.113b



No Chase Aircraft COA Flight Demonstration

Mission Profile



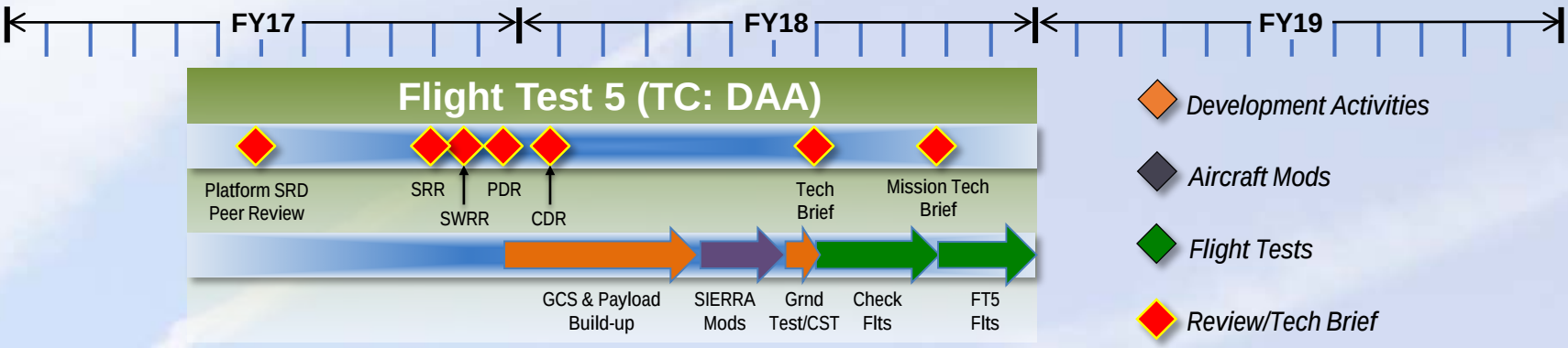
Project Planning for FY18 and FY19

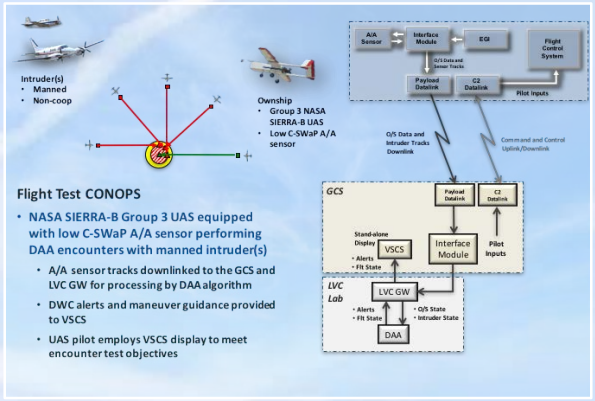
Phase 2 DAA MOPS Development and Validation

Phase 2 DAA and A/A Radar MOPS

- Shifting focus to medium-sized (group 2/3) UAS equipped with a low size, weight and power (SWaP) non-cooperative A/A sensor
  - Cooperative Agreement Notice (CAN) to partner/cost-share with low SWaP A/A sensor manufacturer
  - NASA Ames Systems Integration Evaluation Remote Research Aircraft (SIERRA)-B UAS selected as medium-sized UAS ownship

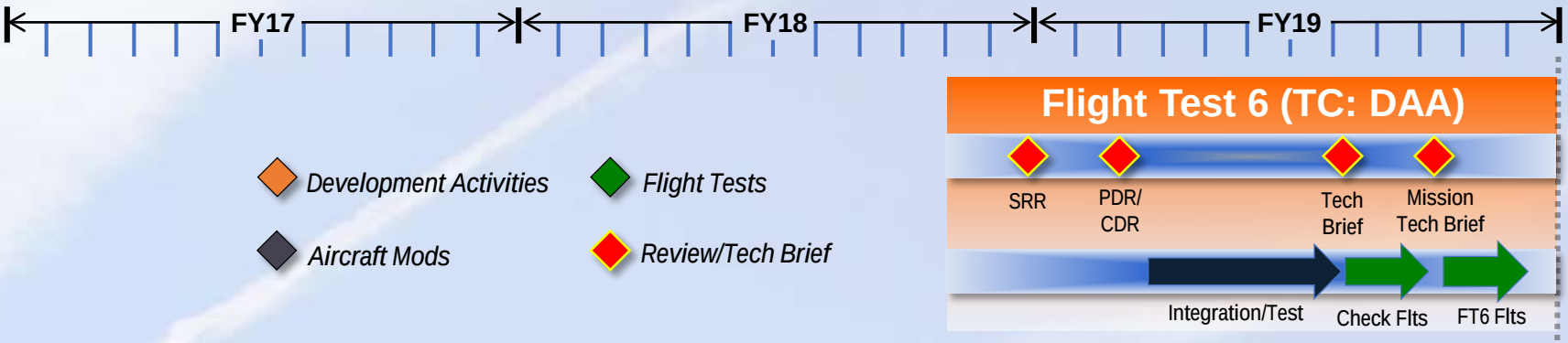
Flight Test Series 5

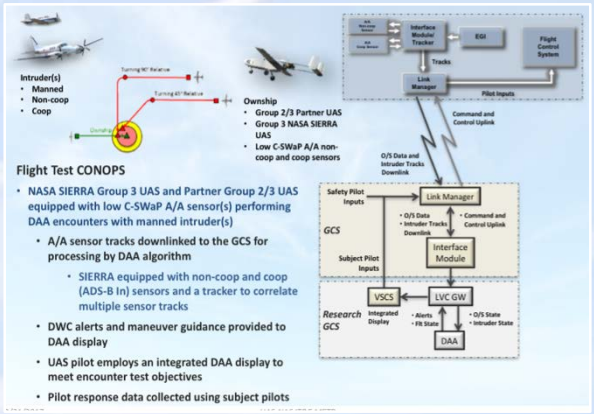




Flight Test Series 5	
Purpose	▪ Initial flight testing of low-cost size, weight and power (C-SWaP) airborne non-cooperative surveillance sensor integrated on group 2/3 UAS
Approach	▪ Equip NASA SIERRA-B UAS with low C-SWaP sensor and perform DAA encounters with manned intruder(s) ▪ Downlink sensor tracks to ground control station (GCS) and LVC Gateway (GW) for processing by DAA algorithm ▪ DAA well clear (DWC) alerts and maneuver guidance provided to Vigilant Spirit Control Station (VSCS) ▪ UAS pilot employs VSCS display to meet test objectives
Test Duration	August-September 2018: ~100 encounters
Tech Transfer	▪ Inform development of Phase 2 MOPS
Project Benefit	▪ Collection of data used by researchers to inform contributions to MOPS

Flight Test Series 6

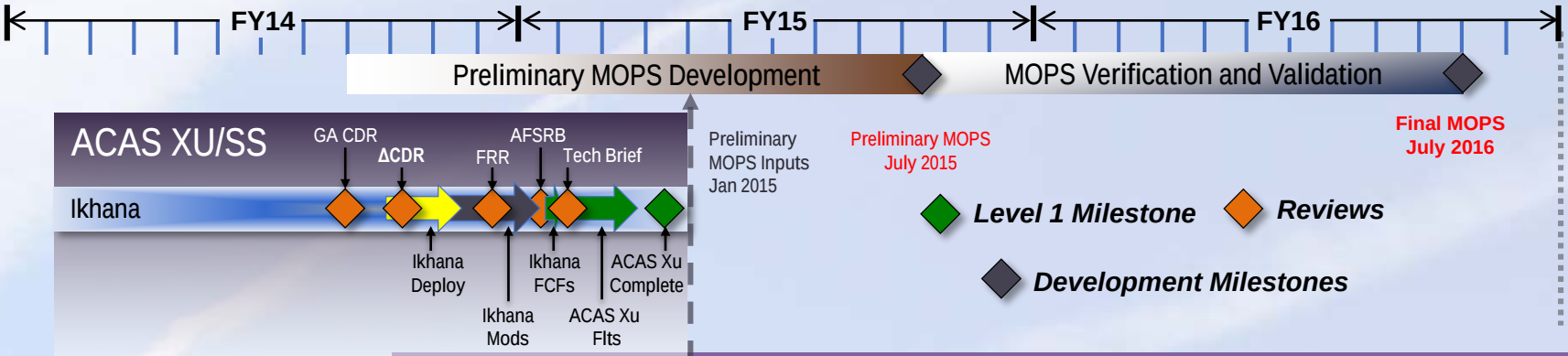




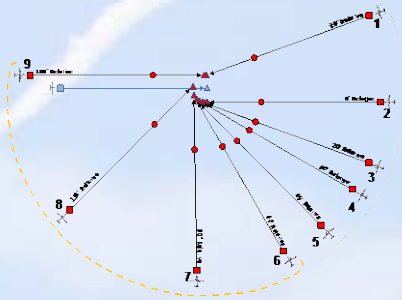
Flight Test Series 6	
Purpose	▪ Operationally representative scenarios and increased emphasis on pilot performance data collection with integration of a NASA research GCS capability
Approach	▪ NASA SIERRA UAS and potential Partner Group 2/3 UAS equipped with low C-SWaP sensor(s) performing DAA encounters with manned intruder(s) ▪ Sensor tracks downlinked for processing by DAA algorithm ▪ SIERRA-B equipped with non-coop and coop (ADS-B In) sensors and a tracker to correlate multiple sensor tracks ▪ DWC alerts/maneuver guidance provided to DAA display ▪ UAS pilot employs integrated DAA display to meet objectives ▪ Pilot response data collected using subject pilots
Test Duration	July-August 2019: ~100 encounters
Tech Transfer	▪ Inform development of final Phase 2 MOPS
Project Benefit	▪ Collection of data used by researchers to inform contributions to MOPS

Backup

2014 ACAS Xu/Self-Separation (SS) Flight Test



ACAS Xu/SS



Horizontal Encounter Geometries

EAFB Restricted Airspace R-2515

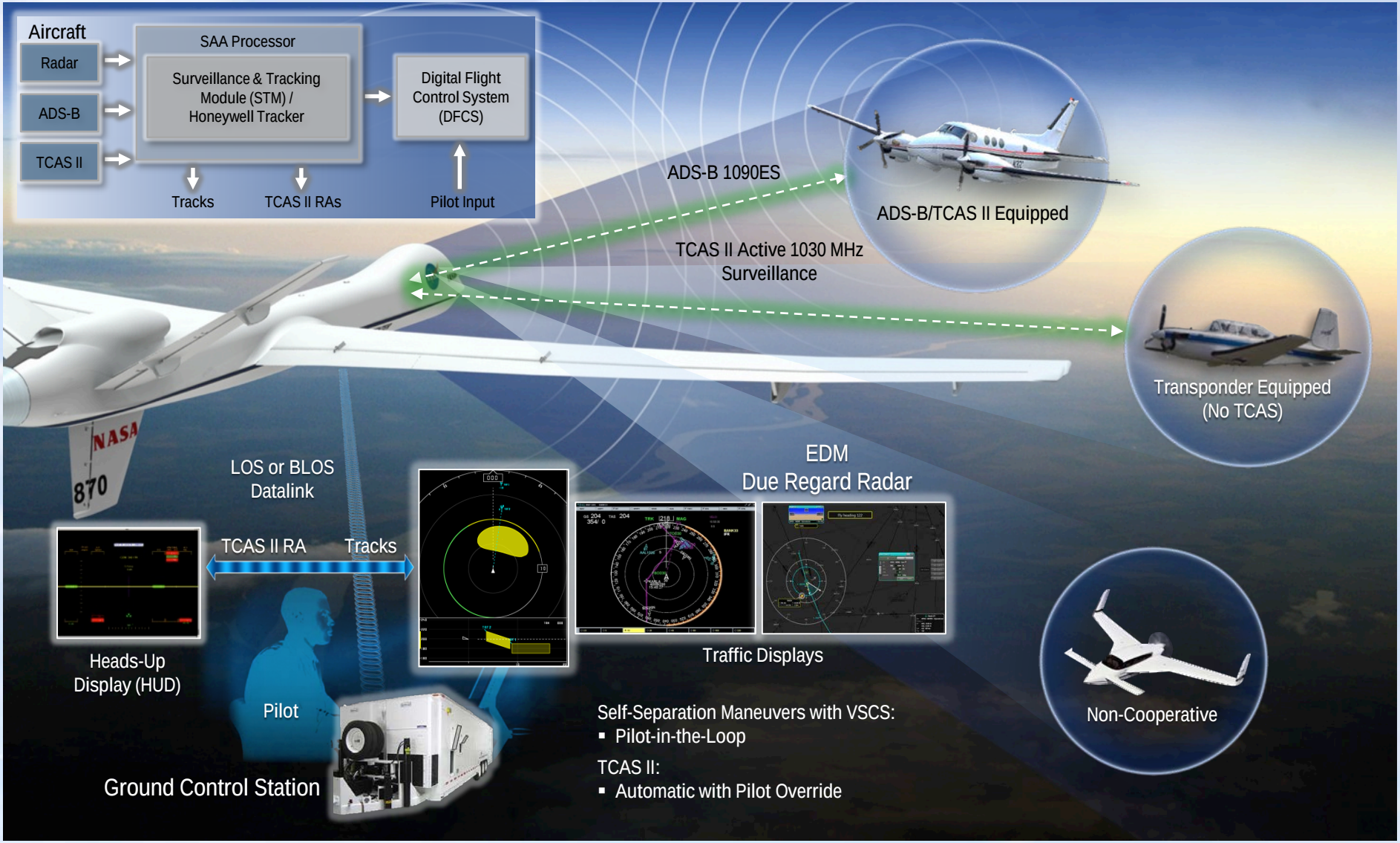
Purpose	▪ Evaluate three DAA algorithms using sensor data for ability to inform UAS pilot of traffic/potential well clear violations in order to resolve conflicts ▪ Evaluate performance of ACAS Xu collision avoidance (CA) algorithms against coop intruders with ADS-B surveillance and non-coop intruders with A/A radar ▪ Demonstrate DAA CONOPS in real-world scenarios ▪ Demonstrate LVC distributed test environment
Approach	▪ Ikhana UAS modified with proof of concept DAA system (prototype A/A radar, sense and avoid (SAA) processor, TCAS, ADS-B, sensor fusion) ▪ Multiple encounter geometries (CA and SS)
Test Duration	November 2014-December 2014 (9 flights) ▪ November 2014: ACAS Xu CA (UAS versus manned) ▪ December 2014: ACAS Xu CA (UAS versus UAS) ▪ December 2014: Self-Separation (UAS versus manned)
Tech Transfer	▪ DAA CONOPS and algorithm flight demonstration ▪ Data for validation of sensor models, well clear definition, and SS/CA interop
Project Benefit	▪ Conduct flight test risk reduction activities for FT3 and FT4 ▪ First live flight test for DAA algorithms and pilot guidance displays for real sensor data/uncertainties, real environmental factors ▪ LVC-Distributed Environment (DE) connectivity to Ikhana GCS established

2014 ACAS Xu Flight Test Summary

- **Four unmanned versus manned CA flights conducted**
  - **Ownship:** Ikhana UAS
  - **Intruders:** FAA Convair 580, Honeywell King Air C90, NASA T-34C
  - Single intruder at a time
  - 85 encounters, 20 hours flight time/data collection
  - First CA system for UAS tested without artificial horizontal or vertical offsets
  - Flight test encounters flown in exact conflict conditions
- **Two unmanned versus unmanned CA flights conducted**
  - **Ownship:** Ikhana UAS
  - **Intruder:** GA-ASI Predator-B
  - 30 encounters, 10 hours of flight time/data collection
  - First CA flight test employing UAS versus UAS encounters
- **Three unmanned versus manned initial SS flights conducted**
  - **Ownship:** Ikhana UAS
  - **Intruders:** Honeywell King Air C90, NASA T-34C
  - Single intruder at a time
  - 55 encounters, 12 hours flight time/data collection
  - Three self-separation algorithms evaluated
  - **VSCS – Autoresolver:** NASA/AFRL, UAS-NAS
  - **Stratway+:** NASA, UAS-NAS
  - **Conflict Prediction and Display System (CPDS):** GA-ASI

Flight Test 3 Overview

Flight Systems



Flight Test 3 Summary

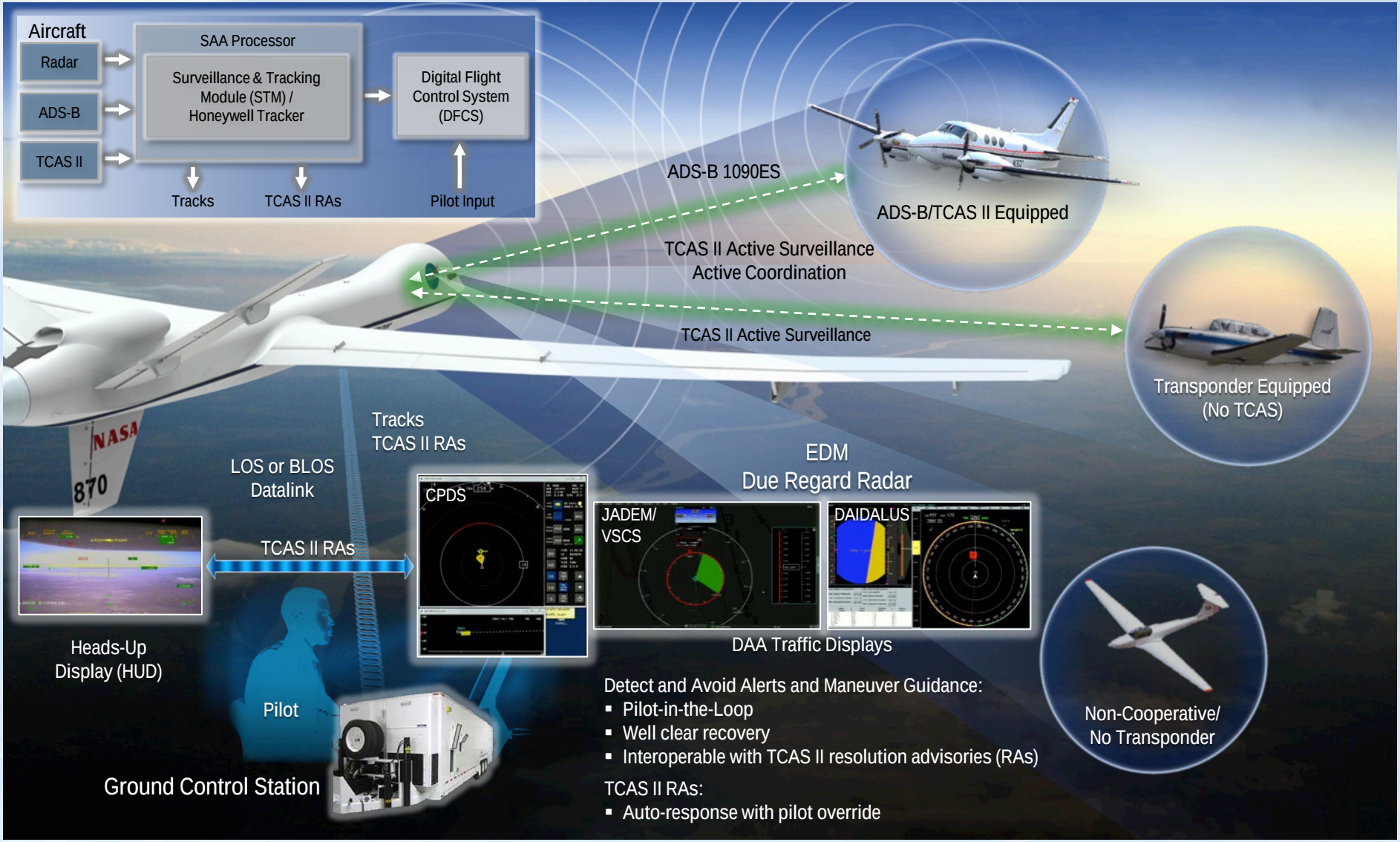
FT3 Flight Operations

- June 17-July 24, 2015
  - › Ikhana versus manned intruder(s)
  - › 11 flights completed
    - More than 200 A/A encounters
    - DAA maneuver guidance and alerting logic checks
    - Auto TCAS II maneuvers
    - Engineering development model (EDM) radar performance near scan volume limits
    - EDM radar low-altitude performance tests
    - Higher closure rate encounters with F/A-18
    - Stressing multi-intruder encounters

	Aircraft		EDM DRR	ADS-B	GPS	TCAS I	TCAS II	CNPC	Notes
Ownships		NASA 870 CFG 1	✓	✓	✓		✓		+ HUD
		NASA 608 CFG 2		✓	✓	✓		✓	
Intruders		NASA 850 CFG 1			✓	✓			Z-12 GPS
		N3GC CFG 1, 2		✓	✓		✓		+ TCAS Recorder
		NASA 865 CFG 1, 2		✓	✓	✓			
		NASA 7 CFG 2		✓	✓	✓			

Flight Test 4 Overview

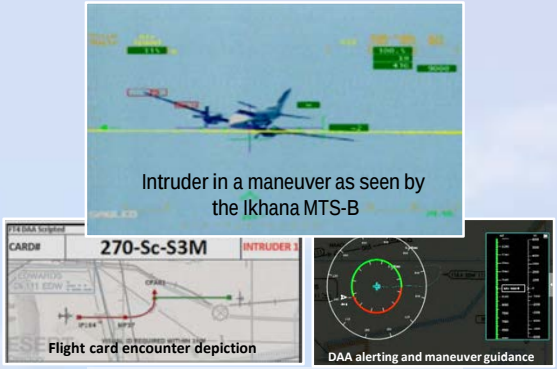
Flight Systems



Flight Test 4 Summary

- Research Objectives:
  - Conduct FT4 integrating the latest Separation Assurance/Sense and Avoid Interoperability (SSI) algorithms, Human Systems Integration (HSI) displays, and LVC test environment to support validation of Phase 1 DAA MOPS
  - Document the performance of the test infrastructure in meeting the flight test requirements

FT4 Flight Assets



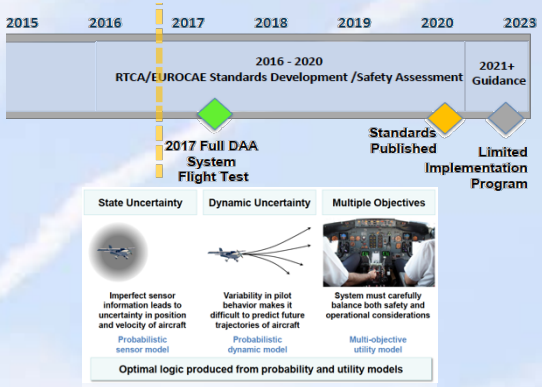
Scripted Encounters

Flight Test Execution

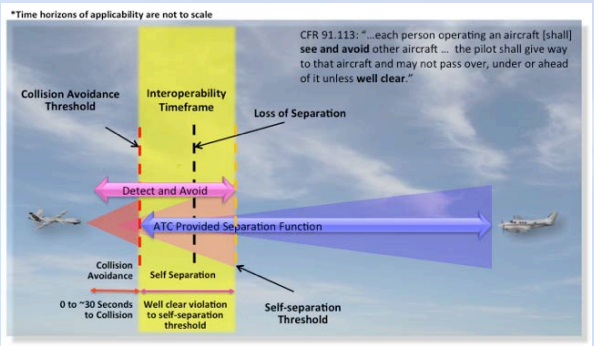
- Results, Conclusions, and Recommendations:
  - FT4 successfully completed June 30, 2016
    - Leveraged lessons learned and risk reduction from technology refinements to support Phase 1 MOPS validation
    - Two system checkout and 19 data collection flight tests
    - 11 weeks (April 12-June 30)
    - 321 A/A encounters
      - 98.1 flight hours on Ikhana
      - 25 pilots and six different intruder aircraft
    - Excellent collaboration between partners
      - GA-ASI, Special Committee (SC)-228 DAA Working Group, Honeywell
    - Nearly 500 gigabytes of data collected
      - Data products provided in an accurate and timely manner to researchers (close of business day of flight test, differential Global Positioning System [DGPS] data next day)
    - In concert with project simulation activities, FT4 contributed significantly to the validation of DAA MOPS; it identified some key performance requirements that needed additional refinement
      - Well clear recovery
      - DAA/TCAS interoperability
    - Flight test report completed
    - Lessons learned documented

ACAS Xu Flight Test 2

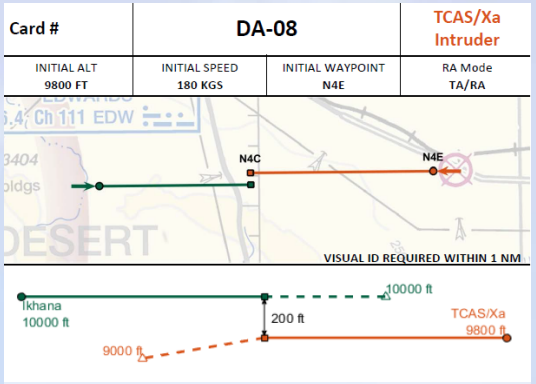
- Flight Test Objectives:
  - Validate modeling and simulations
  - Demonstrate system behavior integrated on prototype avionics and UAS
  - Collect flight test data for performance evaluations and future R&D



Evolve ACAS Xu algorithm



Well clear and collision avoidance functions integrated into one algorithm

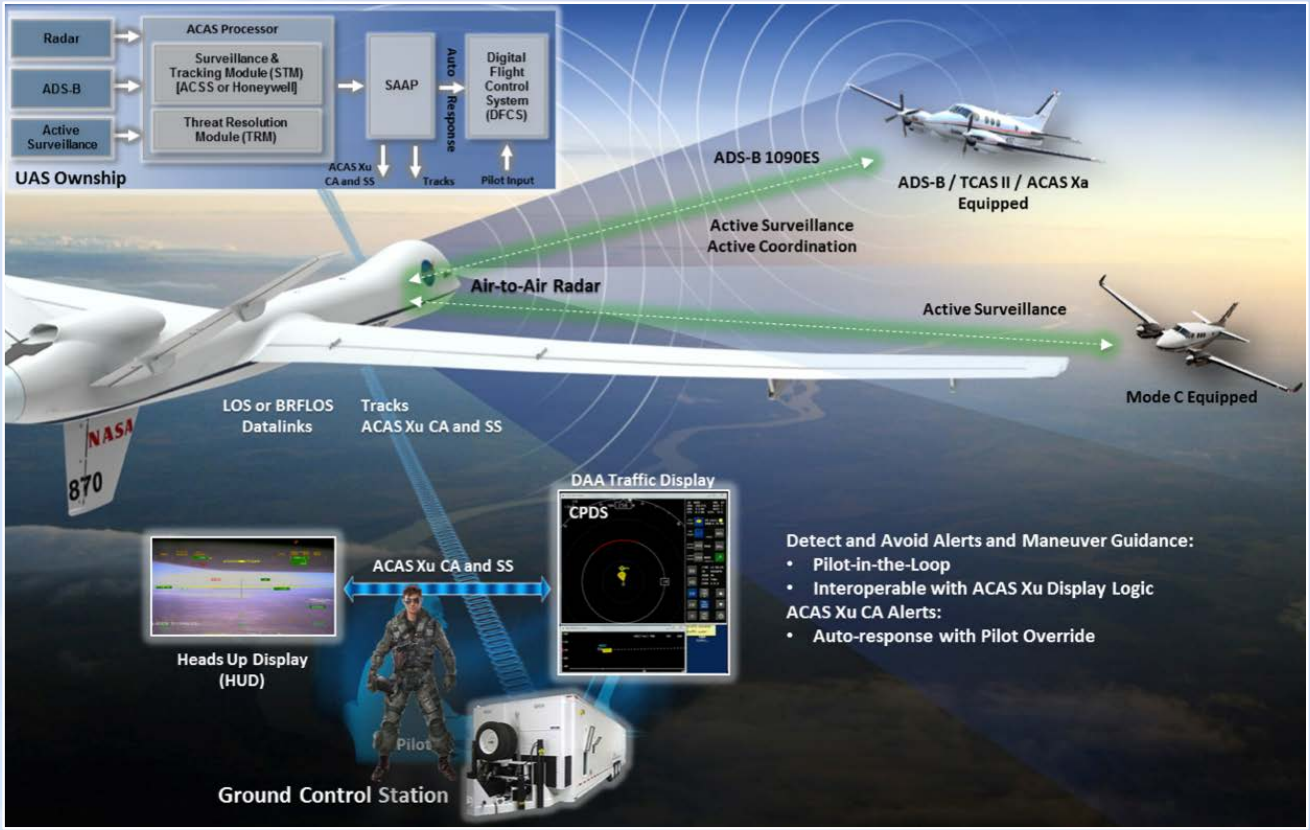


ACAS Xu versus ACAS Xa

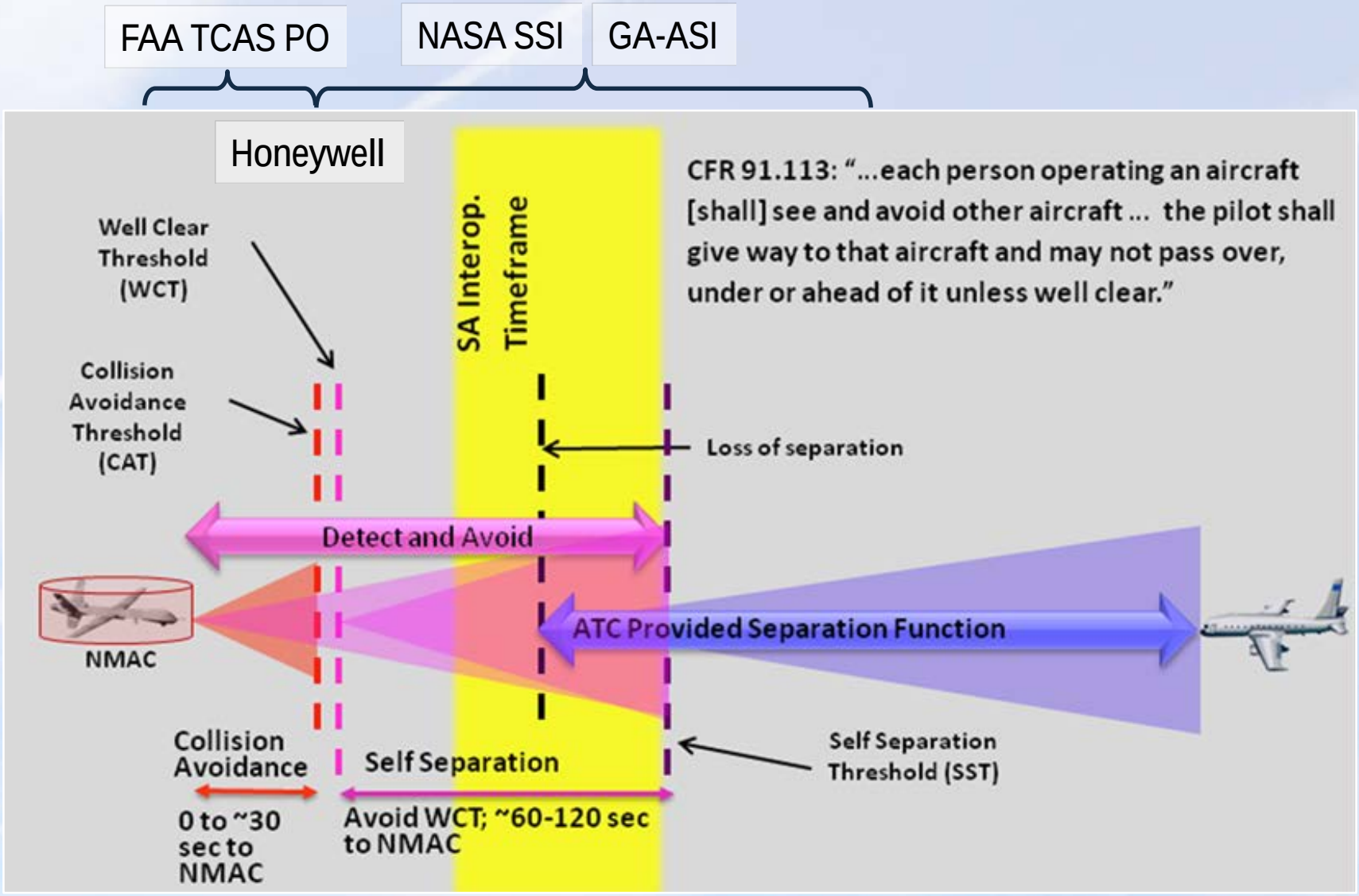
- Flight Test Overview:
  - Continue collaboration with the FAA TCAS Program Office-led partnership to mature the ACAS Xu software in support of ACAS Xu MOPS development (draft FY18, final FY20)
    - FY17 flight tests (mid June-early August)
    - About 220 encounters/ ~13-14 flights (Ikhana as ownship)
    - Intruders provided by Honeywell and Aviation Surveillance & Communications Systems (ACSS)
  - More capable functionality
    - Horizontal and vertical maneuvers against multiple intruders
    - RA logic accounts for sensor quality and ownship performance limitations
    - Includes DAA or SS functionality (Phase 1 DAA MOPS)
    - ACAS processors are representative production units (Honeywell and ACSS)
    - Performance against ACAS Xa (mature system in operational evaluation that will directly replace TCAS II)
    - Ownship low approach operations (data collection only during mission)

ACAS Xu FT2 Overview

- ACAS Xu FT2 leverages off of ACAS Xu 2014 (plus FT3/4)
- ACAS scripted encounters
- Data collection for system under test (SUT):
  - CPDS
  - Honeywell ACAS Xu unit
  - ACSS ACAS Xu unit
  - EDM radar
- Sensor evaluation
  - ACAS Xa/Xu
  - EDM A/A radar
  - Mode C
  - Mode S
  - TCAS II
  - ADS-B
- Multi-intruder requirements
  - King Air C90 (2)



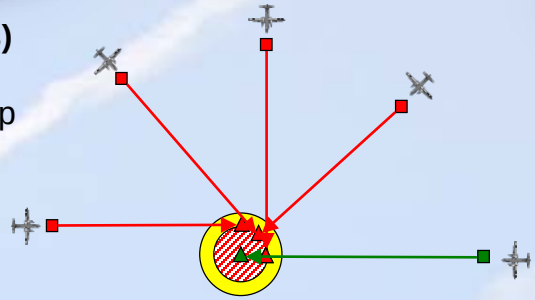
Detect and Avoid Function



* It is possible for the CAT to be greater than the WCT.

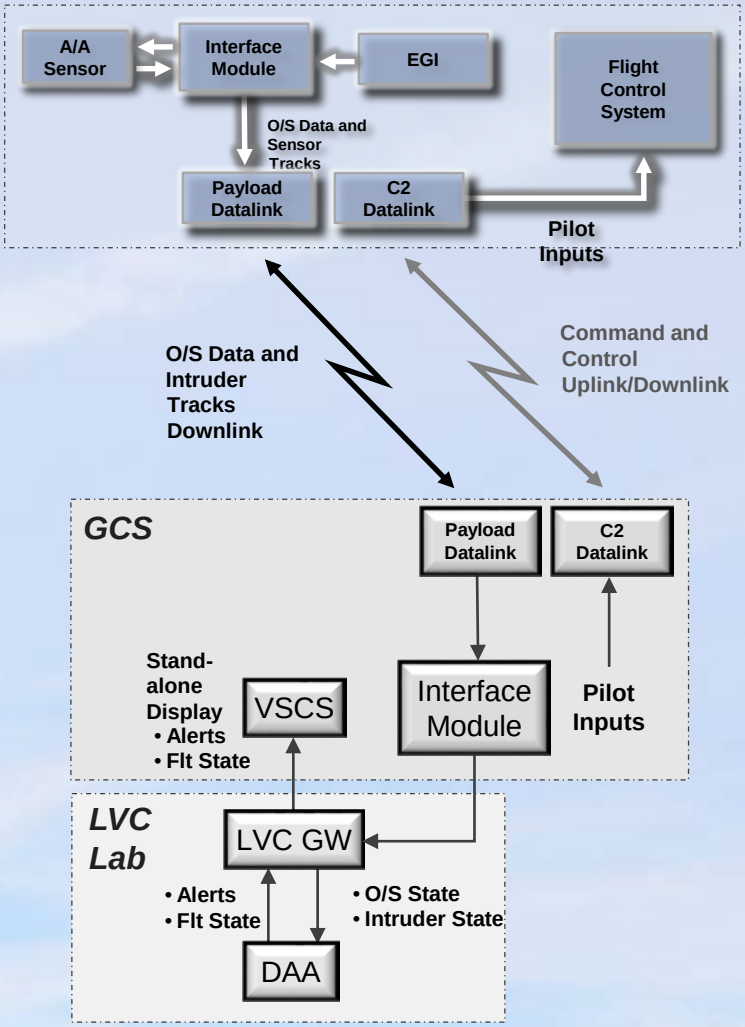
FT5 FY18 Flight Test Operational View – 1 (OV-1)

SIERRA-B UAS with Low C-SWaP A/A Sensor



Intruder(s)
- Manned
- Non-coop

Ownship
- Group 3 NASA SIERRA-B UAS
- Low C-SWaP A/A sensor



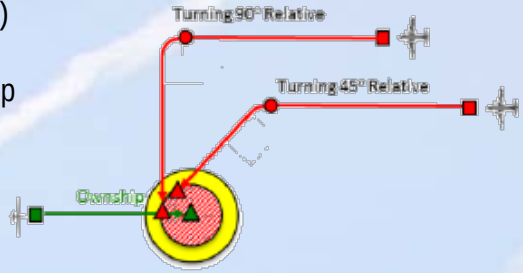
Flight Test CONOPS

- NASA SIERRA-B Group 3 UAS equipped with low C-SWaP A/A sensor performing DAA encounters with manned intruder(s)
  - › A/A sensor tracks downlinked to the GCS and LVC GW for processing by DAA algorithm
  - › DWC alerts and maneuver guidance provided to VSCS
  - › UAS pilot employs VSCS display to meet encounter test objectives

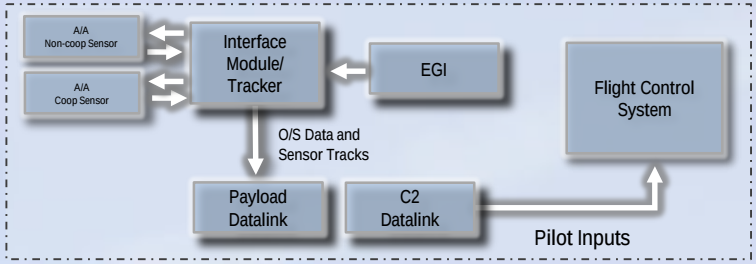
FT6 FY19 Flight Test OV-1

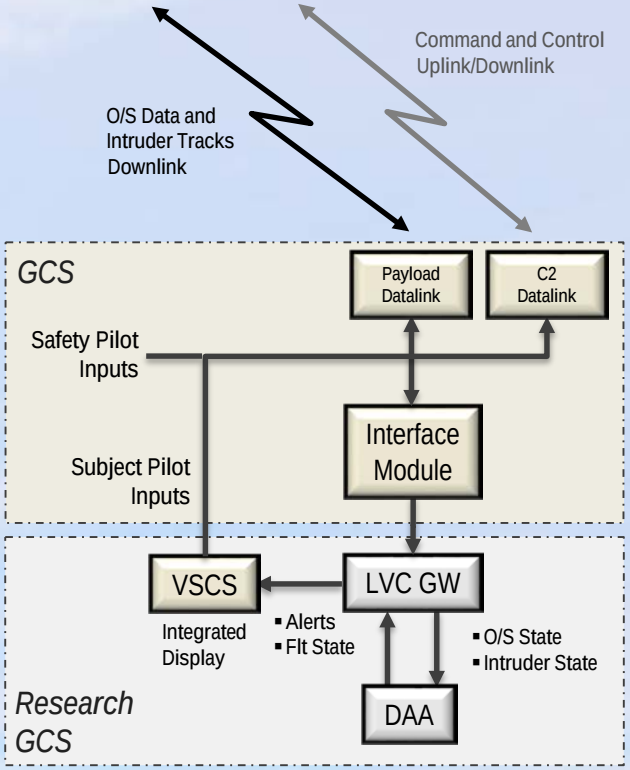
Medium-Sized UAS with Low C-SWaP A/A Sensors

Intruder(s)
- Manned
- Non-coop
- Coop



Ownship
- Group 2/3 partner UAS
- Group 3 NASA SIERRA-B UAS
- Low C-SWaP A/A non-coop and coop sensors

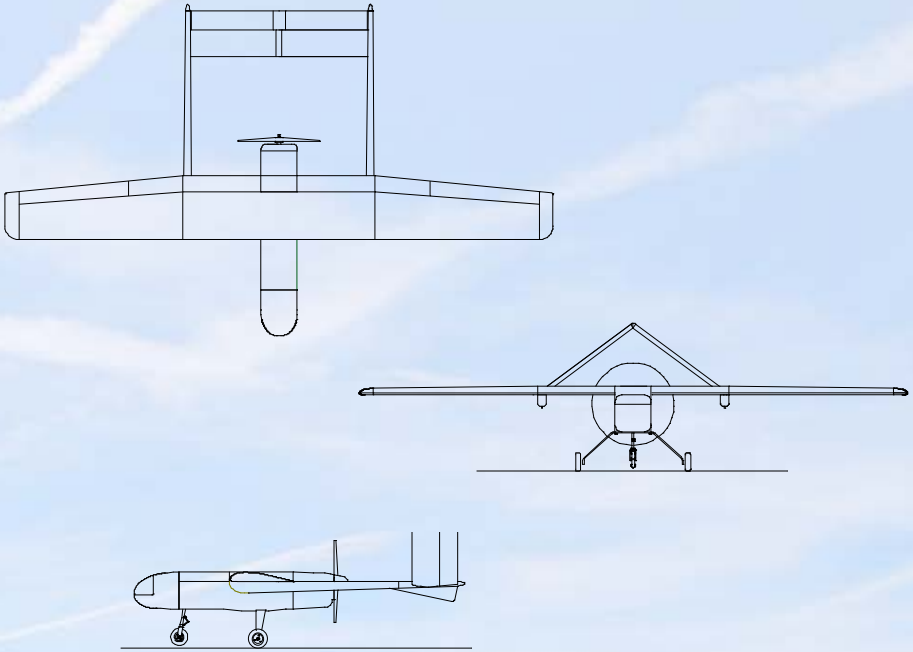




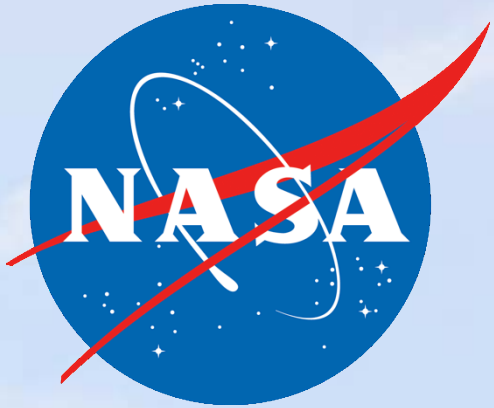
Flight Test CONOPS

- NASA SIERRA Group 3 UAS and partner Group 2/3 UAS equipped with low C-SWaP A/A sensor(s) performing DAA encounters with manned intruder(s)
  - › A/A sensor tracks downlinked to the GCS for processing by DAA algorithm
    - SIERRA-B equipped with non-coop and coop (ADS-B In) sensors and a tracker to correlate multiple sensor tracks
  - › DWC alerts and maneuver guidance provided to DAA display
  - › UAS pilot employs an integrated DAA display to meet encounter test objectives
  - › Pilot response data collected using subject pilots

Sensor Integrated Environmental Remote Research Aircraft (SIERRA)



Wing Span	20 feet
Length	11.8 feet
Height	4.6 feet
Wing Area	42.4 feet^2
Empty Weight	320 pounds
Max Gross Weight	480 pounds
Max Operating Speed (V_{mo})	80 knots
Cruise Speed	55-63 knots
Stall Speed (No flaps V_{so})	48 knots
Aspect ratio	9.43
Rate of Climb (S/L Std Day, Max Gross Wt)	500 fpm
CG Range	27-33% MAC
Payload weight	100 pounds
Payload power	24V DC
Load Rating (Utility)	+4.4 g, -1.7 g
Duration	8-10 hours


NASA